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Catastrophic impact of extreme flood events on the morphology and evolution of the lower Jökulsá á Fjöllum (northeast Iceland) during the Holocene

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The impact of extreme flood events is rarely considered in studies of long-term landscape evolution, despite the potential for catastrophic landscape change in a short period of time. Here, we use an integrated approach of geomorphological mapping, topographic analysis and geophysical surveys to identify and quantify the impact of extreme flood events (jökulhlaups) along the Jökulsá á Fjöllum, Iceland, where evidence for the action of such floods is widespread on microspatial to macrospatial scales. The apex of the 28-km-long Jökulsárgljúfur canyon is characterised by a complex network of palaeo-flood channels and large vertical knickpoints such as Dettifoss (54 m high) and Hafragilsfoss (20 m high). Downstream, the Forvoð valley contains large terraces of boulder-rich deposits (50 m thick, >3 km long). Near the outlet of the canyon is Ásbyrgi, a dry canyon (3 km long, 1 km wide, up to 90 m deep) with eroded cataracts and scabland morphology immediately upstream and ~90 m above the current river channel. Topographic analysis and electrical resistivity tomography surveys show that 0.144 km^3 of rock was eroded from Ásbyrgi during its formation ~10,000 years ago, and just 4% of this eroded volume is currently filled with sediment deposits, up to 5 m thick. Deposited boulders across the canyon floor of Ásbyrgi demonstrate that the discharge of the jökulhlaup that formed the canyon was at least 39,000 $m^3\,s^{-1}$. We present a model for the evolution of the lower Jökulsá á Fjöllum and the Jökulsárgljúfur canyon during various stages of an extreme flood event. Reconstruction of the early Holocene flood event includes the initiation and development of different canyons before the capture of all floodwater within one canyon at the end. We tie the evolution of the lower Jökulsárgljúfur canyon to established chronology of flood events during the Holocene farther upstream and highlight the dominant impact of extreme flood events over background processes in this landscape.

1. Introduction

Extreme flood events are characterised by the release of a large volume of water over the landscape in a short period of time. Such events occur in a range of environments and can be triggered by glacial lake outbursts (e.g., Baker et al., 1993), landslide or moraine dam failures (e.g., Dunning et al., 2006), or by subglacial volcanic eruptions (e.g., Björnsson, 2009; Dunning et al., 2013). Extreme flood events are common over geological timescales, and the potential for geomorphic change during such events is great owing to high peak discharges, potentially over $10^6\,m^3\,s^{-1}$ (Baker, 2002). Previous work has identified the impact of extreme flood events in the evolution of a range of terrestrial environments such as the Channeled Scabland of northwestern USA following the draining of Glacial Lake Missoula (Bretz, 1923), the Tsangpo gorge of southeastern Tibet (Montgomery et al., 2004), and the Transbaikalia and Altai Mountains of Siberia (Carling et al., 2009a; Margold et al., 2011); it has also been suggested that such floods could have played a key role in the evolution of the Straits of Gibraltar (Garcia-Castellanos et al., 2009), the English Channel (Gupta et al., 2007), and the surface of Mars (Warner et al., 2010, 2013). Despite this, current landscape evolution models do not consider the impact of extreme flood events in controlling bedrock landscape morphology (Carling et al., 2009b). Detailed quantitative studies of the impact of extreme flood events on the landscape are therefore required.

Glacial outburst floods, termed 'jökulhlaups', occur regularly in Iceland owing to the location of large ice caps atop active volcanoes (e.g., Björnsson, 2002), which makes Iceland a globally important place to study the impact of extreme flood events. Previous work on Icelandic jökulhlaups includes the interpretation of deposited sediments (e.g., Maizels, 1997; Duller et al., 2008; Marren et al., 2009), the reconstruction of the hydraulic conditions (e.g., Baker et al., 1993; Alho et al., 2005, 2010; Carrivick, 2006, 2007), and the geomorphic impact of jökulhlaups in proglacial areas close to the floodwater source

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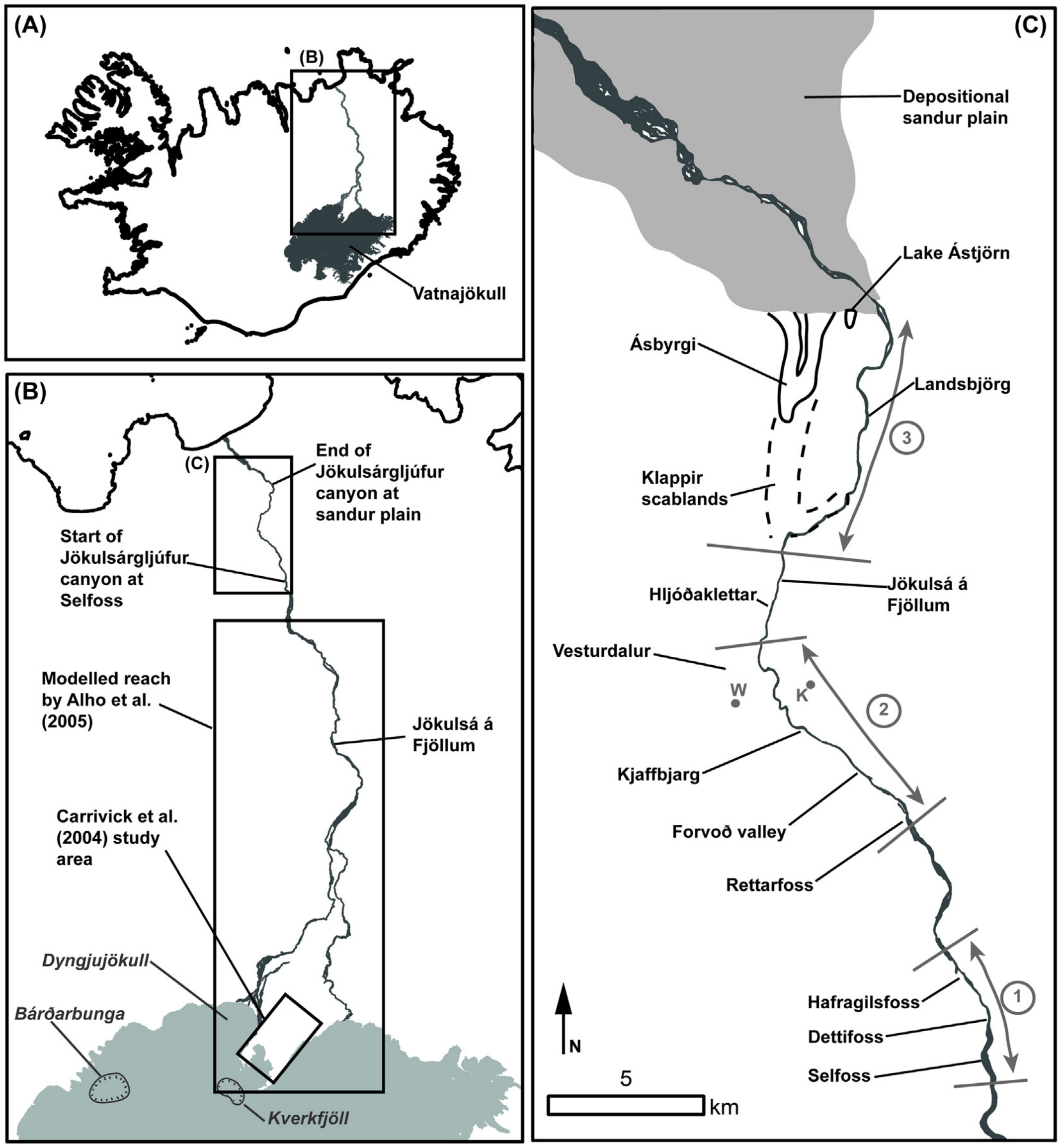

Fig. 1. (A) Outline of Iceland with Vatnajökull ice cap (grey-shaded area), the source of the floodwaters, and the course of the present day Jökulsá á Fjöllum draining to the north coast. (B) Zoomed in map showing the areas studied by previous authors (Carrivick et al., 2004; Alho et al., 2005) in the upper and middle reaches of the Jökulsá á Fjöllum as well as the Jökulsárgljúfur canyon, the focus of this study. Kverkfjöll and Bárðarbunga volcanic centres are highlighted. Grimsvötn volcano is located ~25 km south of Bárðarbunga, just beyond the extent shown in the map. (C) The Jökulsárgljúfur canyon is divided into three sections for the study: (1) the apex of the Jökulsárgljúfur canyon between Selfoss and Hafragilsfoss; (2) the Forvoð valley, containing depositional landforms; and (3) the lowermost section of the Jökulsárgljúfur canyon, with the Ásbyrgi horseshoe and the Klappir scabland system. The grey points labelled 'W' and 'K' indicate the location of the sedimentary sequences discussed in Waitt (2002) and Kirkbride et al. (2006), respectively.

(e.g., Magilligan et al., 2002; Carrivick et al., 2004; Dunning et al., 2013). Our current understanding of canyon formation and bedrock erosion processes during extreme flood events is limited, especially in distal areas, and is based on studies such as that of the Channeled Scabland in Washington, USA (e.g., Baker and Kale, 1998) and a small number of studies in Idaho, USA (Lamb et al., 2008, 2014; Lamb and Dietrich, 2009) where the main motivation was to use the terrestrial landscape to infer the formation mechanisms of morphologically similar canyons on Mars. Building on a recent work in the upper reaches of the Jökulsárgljúfur canyon, Iceland (Baynes et al., 2015), the aim of this study is to reconstruct the bedrock landscape evolution of the lower Jökulsá á Fjöllum, in particular the impact of extreme flood events that are known to have occurred since deglaciation (Thórarinsson, 1950; Sæmundsson, 1973; Tómasson, 1973; Eliasson, 1974, 1977; Sigbjarnarson, 1996; Waitt, 2002; Kirkbride et al., 2006; Baynes et al., 2015). This objective is achieved through documenting an inventory of landscape features within the Jökulsá á Fjöllum that are characteristic of the work of extreme floods, establishment of the chronology of floods, and assessment of the geomorphic impact of these extreme flood events during the Holocene using topographic analysis and Electrical Resistivity Tomography (ERT) surveys.

2. Study area

The Jökulsá á Fjöllum is one of Iceland's largest rivers, draining much of the 8100 km^2 Vatnajökull ice cap in the south of the island and flowing 206 km north across central Iceland to the Arctic Ocean (Fig. 1A). The Jökulsá á Fjöllum has experienced multiple jökulhlaups of varying magnitude since the Last Glacial Maximum, with peak discharge for the largest flood estimated at 0.9×10^6 m^3 s^{-1} (Alho et al., 2005; Carrivick et al., 2013). Jökulhlaups occur along the Jökulsá á Fjöllum as a result of either subglacial volcanism beneath Vatnajökull from one or more of the Kverkfjöll, Grimsvötn, or Bárðarbunga volcanic centres (Björnsson, 2009) or the release of floodwater from an ice-

Table 1
Table of geomorphological evidence used for identifying the impact of extreme flood events in bedrock channels (adapted from Carrivick et al., 2004); modifications include the addition of boulder terraces in 'macroscale landforms' and recent studies, e.g., Lamb et al. (2008, 2014).

Scale	Geomorphological feature for distinguishing bedrock-channelled jökulhlaups	Selected references
Macroforms	– Anastomosing channel pattern of valley-wide palaeo-channels cut into bedrock	Kehew and Lord (1986); Rudoy (2002); Waitt (2002); Gupta et al. (2007); Baynes et al. (2015)
	– Deep trench-shaped valleys	Kehew and Lord (1986); Lamb et al. (2008, 2014)
	– Cataracts	Baker (1973); Kehew and Lord (1986); Rudoy (2002); Lamb et al. (2008, 2014); Baynes et al. (2015)
	– Flow overspilling previous drainage divides	Shakesby (1985); Kehew and Lord (1986)
	– Scoured surface	Kehew and Lord (1986); Lamb et al. (2008, 2014)
	– Boulder terraces	Baker (1973); O'Conner (1993)
Mesoforms	– Streamlined residuals	Baker (1988); Komar (1984); Wiedmer et al. (2010)
	– Obstacle and iceblock marks	Baker (1973); Fay (2002)
	– Wash limits	Maizels (1995)
	– Boulder surfaces and boulder bars	Baker (1973); O'Conner (1993)
	– Dunes	Baker (1973); Maizels (1995); Carling (1996); Wiedmer et al. (2010)
	– Bars	Carling et al. (2002)
	– Kettled surfaces	Fay (2002)
	– Slackwater deposits	Baker (1973); Baker and Bunker (1985)
Microforms	– Potholes, flutes, furrows, obstacle marks, and grooves	Hancock et al. (1998); Whipple et al. (2000); Richardson and Carling (2005); Wilson and Lavé (2014)

dammed lake to the south of Kverkfjöll (Björnsson, 2002) (Fig. 1B). Attempts have been made to identify and interpret the impact of jökulhlaups in the Jökulsá á Fjöllum in recent history (Isaksson, 1985; Russell and Knudsen, 2002) and during the Holocene (Thórarinsson, 1950; Sæmundsson, 1973; Tómasson, 1973; Eliasson, 1974, 1977; Sigbjarnarson, 1996; Waitt, 2002; Carrivick et al., 2004; Kirkbride et al., 2006; Baynes et al., 2015). Much of the recent work on this river has focussed on the geomorphic impact and sedimentary evidence of jökulhlaups close to the floodwater source (e.g., Carrivick et al., 2004; Carrivick, 2007; Marren et al., 2009) and on modelling the hydraulic conditions of the floods in mid-stream to upstream reaches (e.g., Alho et al., 2005; Carrivick, 2006, 2007; Carrivick et al., 2013). Baynes et al. (2015) identified evidence for large-scale, rapid canyon cutting within the Jökulsárgljúfur canyon during three erosive periods in the Holocene, using cosmogenic nuclides concentrations to date the exposure of fluvially sculpted bedrock surfaces.

Three distinct reaches are identified within the Jökulsárgljúfur canyon, each exhibiting evidence for extreme flood events (Fig. 1C). The first reach is the main study area of Baynes et al. (2015) at the head of the canyon. There, the Jökulsá á Fjöllum becomes deeply incised into the surrounding terrain, with three large waterfalls over a 5-km-long reach: these are Selfoss (13 m high), Dettifoss (54 m high), and Hafragilsfoss (20 m high); the canyon was carved through the retreat of these waterfalls during extreme floods. Downstream of this reach is the Forvoð valley, where widespread evidence for deposition of large volumes of sediment during extreme floods is present. At the lower end of the Jökulsárgljúfur canyon, additional evidence is present for the erosive impact of extreme flood events with the Klappir scabland area and Ásbyrgi canyon, a large dry cataract now disconnected from the current course of the Jökulsá á Fjöllum. This area contains outstanding preservation of large-scale fluvial landforms that have not undergone any alteration since their formation and therefore offer an excellent opportunity to quantify the impact of extreme floods. Downstream of this reach, the Jökulsá á Fjöllum flows for 18 km over a large depositional sandur plain to the coast. The geology of the area is characterised by young (<0.8 Ma) basalt lava flows stacked on top of each other, ranging in structure from regular, near-vertical columns with metre-scale joint spacing to blocky, rubbly lavas with a centimetre to decimetre scale jointing. The ages of abandoned bedrock surfaces

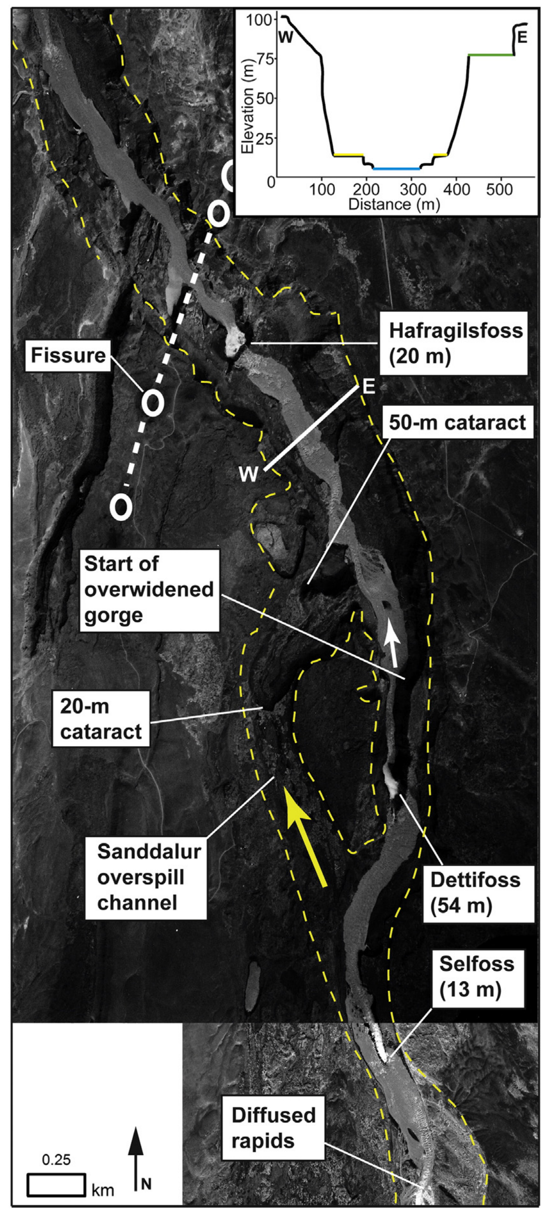

Fig. 2. Aerial photograph showing the upper 5 km of the Jökulsárgljúfur canyon where the Jökulsá á Fjöllum is deeply incised with three vertical waterfalls; Selfoss (13 m in height), Dettifoss (54 m in height), and Hafragilsfoss (20 m in height) (adapted from Baynes et al., 2015). The dashed yellow lines indicate the areas where evidence for erosion during extreme flood events is clear. The 200-m-wide Sanddalur overspill channel contains a 20-m vertical cataract and a 50-m vertical cataract where it rejoins the main canyon. The fissure that erupted 8.5 ka ago (Eliasson, 1974) is highlighted with white circles, and a cross section of the gorge across the line from W to E is inset. With the exception of the 500 m of canyon immediately downstream of Dettifoss, the Jökulsá á Fjöllum does not fill the canyon, suggesting that the flow was much greater when the canyon was formed. Aerial photograph source: Landmælingar Íslands. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

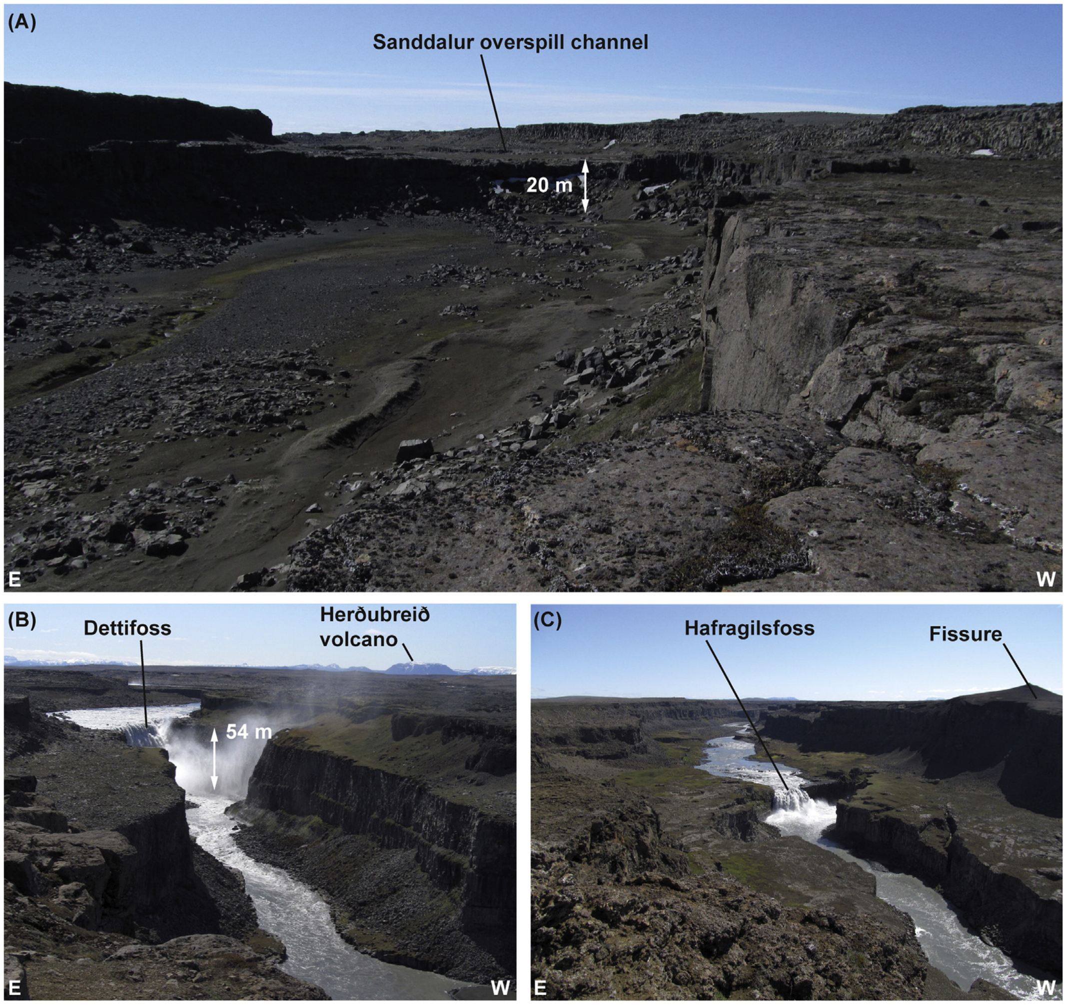

Fig. 3. Evidence for the impact of extreme flood events in the upper reach of the Jökulsárgljúfur canyon. (A) Looking upstream (south): the Sanddalur overspill channel contains clear fluvially sculpted surfaces and a 20-m dry cataract. (B) Looking upstream toward Dettifoss (54 m in height): the Jökulsárgljúfur canyon contains three large vertical waterfalls formed by the upstream retreat of knickpoints through the toppling of basalt columns. (C) Looking upstream toward Hafragilsfoss (20 m in height) from the location of the fissure that erupted 8.5 ka ago (Eliasson, 1974): the canyon cuts through the fissure, providing an independent constraint on the age of the canyon as all of the erosion has occurred since the fissure erupted. Strath terraces, indicating the palaeo-location of the river bed, can be seen on the edges of the canyon. Long stretches of these terraces have been exposed at the same time, including the Sanddalur overspill channel (Baynes et al., 2015).

show significant canyon formation occurred at Ásbyrgi ~10,000 years ago and at the head of the Jökulsárgljúfur canyon ~5000 and ~1500 years ago through the upstream migration of large knickpoints such as Dettifoss and Selfoss (Baynes et al., 2015).

3. Morphological and sedimentological evidence for extreme floods along the Jökulsá a Fjöllum downstream of Selfoss

Carrivick et al. (2004) created a list of key criteria to identify the occurrence of extreme floods in bedrock channels, from macroscale landforms such as cataracts and anastomosing channels to microforms such as potholes and flutes (Table 1). Notably, many of the landforms listed in Table 1 are not exclusive to the action of extreme flood events, and the presence of these landforms within a landscape should not necessarily lead to the conclusion that an extreme flood event has taken place (Carrivick et al., 2013). However, considering the landscape as a whole and how multiple landforms are 'associated' to each other across a range of spatial scales can give an insight into the magnitude of the events that formed them (Carling et al., 2009c). We use the criteria in Table 1 to document erosional and depositional landforms in the study landscape using field observations and aerial photographs. The following sections describe this evidence in each of the three study reaches (Fig. 1C): (i) Selfoss to Hafragilsfoss, (ii) the Forvoð valley, and (iii) Ásbyrgi and the Klappir scablands.

3.1. Selfoss to Hafragilsfoss

From the apex of the Jökulsárgljúfur canyon at Selfoss to ~5 km farther downstream, the Jökulsá á Fjöllum becomes deeply incised into the surrounding terrain (Fig. 2). Exposed in the canyon wall ~4 km downstream of its head is a volcanic conduit that brought lava to the surface in a fissure eruption about 8.5 ka BP (Eliasson, 1974). This event provides an independent constraint on the maximum age for the formation of the canyon upstream of the fissure and indicates that at least 4 km of the canyon was cut in the last 8.5 ka. In this section, a clear pattern of multiple palaeo-channels has been cut into bedrock, including the Sanddalur overspill channel (200 m wide) that contains a 20-m-high cataract, a dry vertical waterfall characteristic of erosion during jökulhlaups (Carrivick et al., 2004; Lamb et al., 2008, 2014) (Fig. 3A), and a 50-m-high cataract where the channel rejoins the western wall of the main canyon. The vertical headwalls of the three waterfalls in the active channel are also characteristic of the migration

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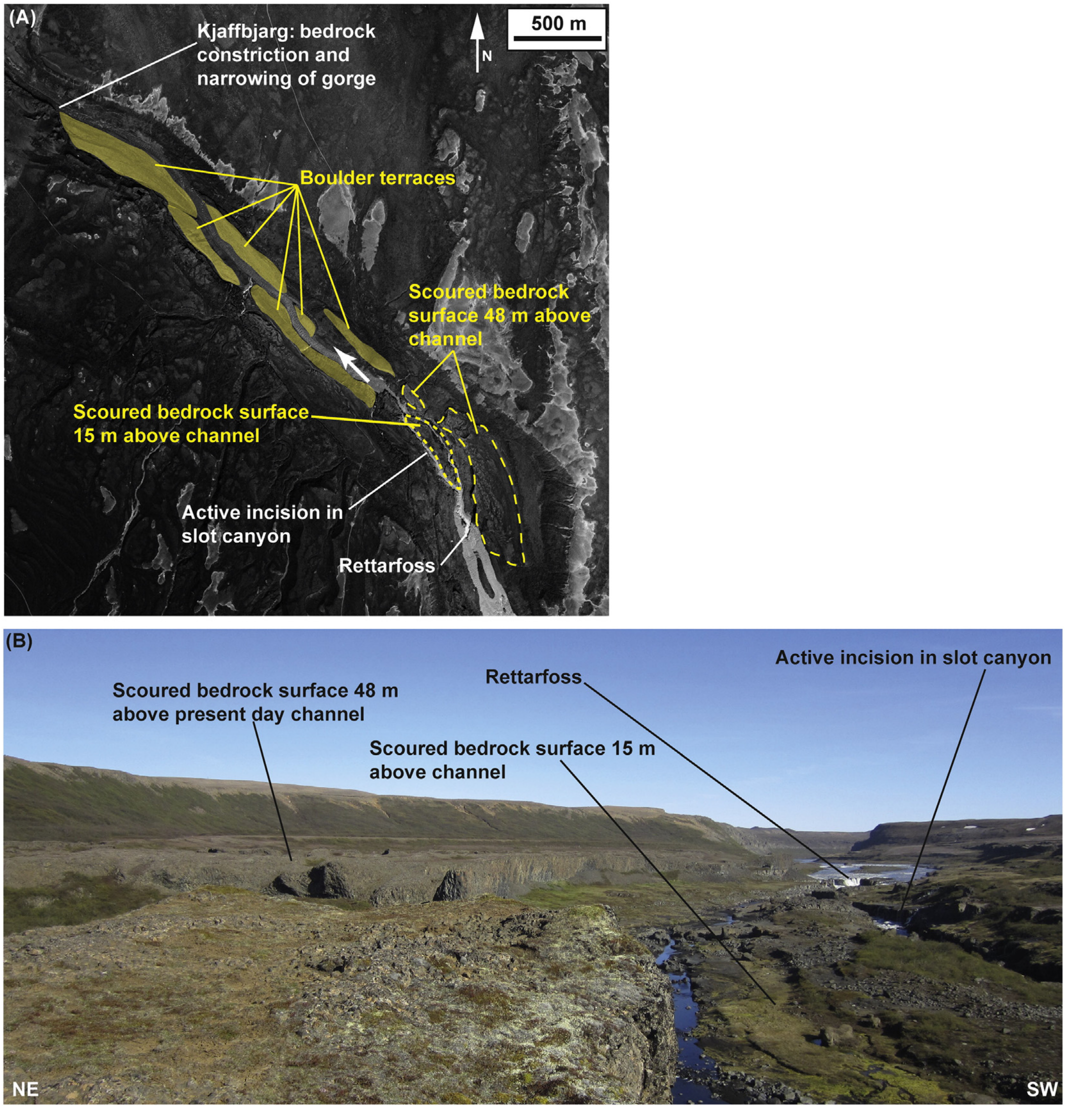

Fig. 4. (A) Aerial photograph of the Forvoð valley. Rettarfoss, the waterfall in the upstream part of a narrow, actively incising slot canyon, is highlighted. The dashed yellow lines indicate the heavily scoured bedrock surface 48 m above the current river channel and a lower bedrock terrace abandoned in the 1950s (Vatnajökulsþjóðgarður National Park Tourist Information). The yellow-shaded areas identify the large boulder terraces, thought to have been deposited during an extreme flood event, possibly owing to a backwater effect as a result of water ponding up behind the narrow bedrock constriction at Kjaffbjarg (also highlighted). Aerial photograph source: Landmælingar Íslands. (B) Looking upstream toward Rettarfoss waterfall, showing the upper part of the Forvoð valley and the strath terraces identified in (A). The surface is heavily scoured owing to the rubbly nature of the bedrock. The columns are thin, not well developed, and fractured such that joint spacing between blocks rarely exceed 30 cm, making blocks easily plucked and transported. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of knickpoints in columnar basalt environments during large floods (Lamb and Dietrich, 2009; Baynes et al., 2015) (Fig. 3B). Further macro-scale evidence for the action of extreme flooding is the relative size of the contemporary river compared to the size of the canyon. With the exception of the 500-m reach immediately downstream of Dettifoss, the Jökulsá á Fjöllum does not fill the canyon floor, even during regular annual spate stages (peak annual discharge from 1973–1979 was ~500 m^3 s^{-1} at Grimsstadir, 25 km upstream of Selfoss; Schunke, 1985) (Fig. 3C). This underfit suggests that the canyon was formed when the flow in the river was significantly greater. Three distinct strath terrace levels are present within the canyon, indicating the palaeo-location of the river bed (Baynes et al., 2015). All of these terraces, and the contemporary river bed, correspond to the top of lava flows. Despite small-scale fluting (on the scale of tens of centimetres) and submeter scale scouring on the strath terraces, evidence is limited for widespread vertical incision of the channel into the lava flows through abrasion. This fact demonstrates that the dominant mechanism of canyon erosion is the upstream propagation of knickpoints through the toppling and subsequent transportation of bedrock columns, once the flow depth has surpassed a threshold value (Baynes et al., 2015).

3.2. Forvoð valley to Vesturdalur

Nine kilometres downstream of the apex of the Jökulsárgljúfur canyon is the Forvoð valley, which contains landforms that testify to the action of extreme flood events in erosional and depositional contexts (Fig. 4A). Downstream of the Rettarfoss waterfall, the river is incised in a relatively narrow valley (20 m wide); 48 m above the current river channel on the eastern side of the valley is an extensive, heavily scoured bedrock surface with relief of up to a few metres (Fig. 4B); this surface was likely formed and then abandoned during an extreme flood (Waitt, 2002), and the high amplitude relief may be the result of efficient plucking promoted by the small size of the basaltic columns and intense fracturing, making blocks with size rarely exceeding 30 cm available for transport. Downstream of the slot canyon, the valley widens and landforms associated with deposition rather than erosion

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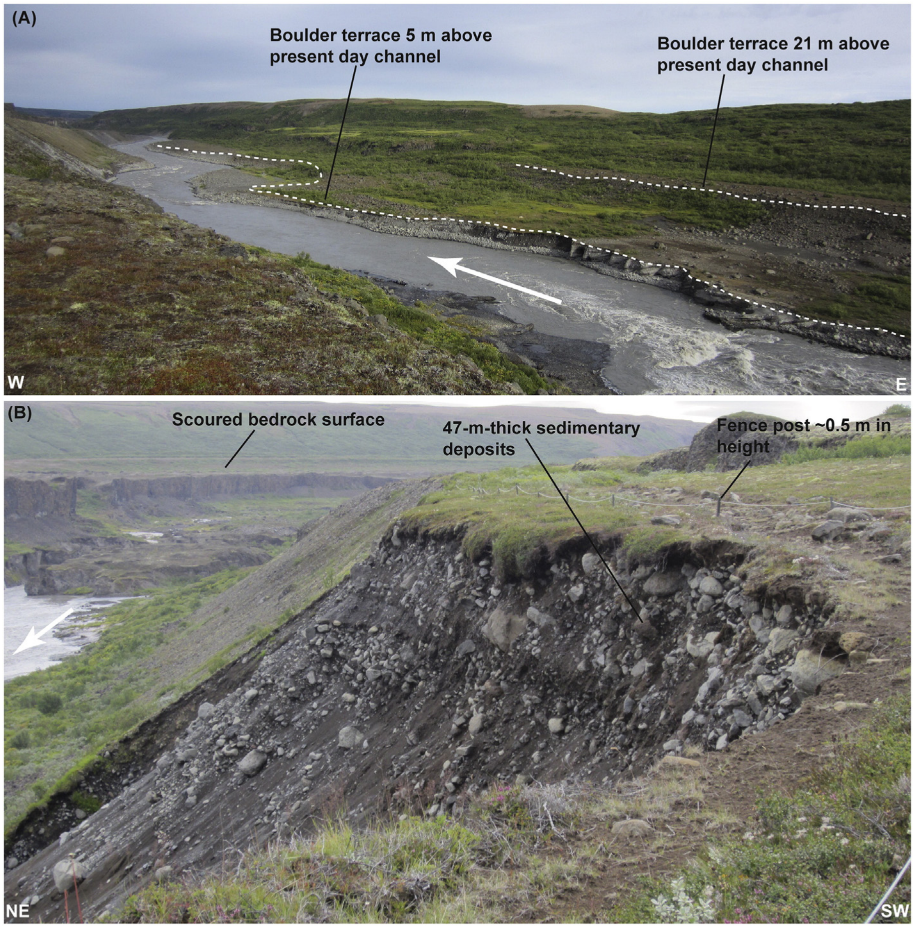

Fig. 5. Within the Forvoð valley, large boulder-rich terraces are exposed on both sides of the valley. On the eastern side of the valley, two terraces made up of sediment containing abundant large boulders are located 5 and 21 m above the current river level as seen in (A). The white arrow indicates the direction of flow of the river. On the western side of the valley, one large fill terrace is present that is 47 m thick and contains boulders with diameter >1 m, shown in picture (B) (taken looking upstream); the scoured bedrock terrace from Fig. 4 is shown in the background of the photograph. For scale, the fence posts on the top of the deposits are ~0.5 m high.

are evident. Boulder surfaces and boulder bars are defined by Carrivick et al. (2004) as 'mesoform' evidence for the action of extreme floods (Table 1), although they should also be considered on the macroscale here as they extend on both sides of the Forvoð valley for >3 km and some of the deposits are up to 50 m thick (Fig. 5). On the western side of the river, boulder-rich deposits up to 47 m thick (some blocks >1 m in diameter) are found above the current river level; and two clear boulder-rich terraces are located on the eastern side of the valley, 5 m and 21 m above the river bed, respectively (Fig. 5). Such extensive, thick, and coarse deposits are likely associated with extreme palaeoflow conditions (Wohl, 1992). We suggest that the boulder-rich sediment deposited in the Forvoð valley is a result of floodwaters losing energy as they pond behind the forced narrowing caused by the bedrock constriction at Kjaffbjarg (Fig. 4A). Subsequent stages of the flood, or subsequent floods, have reworked the boulder-rich deposits in the valley, incising through them but preserving the terrace surfaces high on the valley sides.

Downstream of the Kjaffbjarg bedrock constriction, the Jökulsá á Fjöllum flows within a deeply incised scabland area at Vesturdalur (Fig. 1C) before flowing along the eastern edge of another post-glacial volcanic fissure at Hljóðaklettar (Eliasson, 1974; Waitt, 2002). Vesturdalur is a key location of previous studies that have identified extreme flood events along the Jökulsá a Fjöllum. Waitt (2002) and Kirkbride et al. (2006) identified sedimentary sequences containing sandy flood deposits from this location (Fig. 1C). Waitt (2002) identified up to 16 sandy flood layers high above the west side of the Jökulsá á Fjöllum thought to have been laid down between 8000 and 4000 years ago, constrained by the presence of H4 and H3 tephra layers in the sequence that were deposited following eruptions of Hekla volcano ~3800 YBP and ~2900 YBP, respectively (Kirkbride et al., 2006). Two flood layers in a sequence on the eastern side of the valley, corresponding to the layers at the top of the sequence identified by Waitt (2002), were dated by Kirkbride et al. (2006) to 5020 and 4610 cal. YBP. This sedimentary evidence suggests that multiple large flood events affected this part of the canyon during the mid-Holocene.

3.3. Ásbyrgi and Klappir scablands

Perhaps the most striking evidence for erosion during extreme floods along the Jökulsá á Fjöllum can be found at Ásbyrgi canyon and the Klappir scablands. Ásbyrgi is a horseshoe-shaped canyon (3 km long, 1 km wide, up to 90 m deep), which is disconnected from the current river that now flows in a deeply incised canyon at Landsbjörg to the east (Figs. 1C, 6). Between Ásbyrgi and the main Jökulsárgljúfur canyon is Lake Ástjörn, a small cataract now filled with water, that exhibits the same amphitheatre shape as Ásbyrgi albeit on a smaller scale (250 m wide). Upstream of Ástjörn is a narrow scabland tract leading from the main Jökulsárgljúfur canyon but hanging ~60 m above the modern river. Ásbyrgi has been cut into a succession of lava flows with a northward dipping surface (slope: 0.025). The Klappir scablands are a flood-scoured area of bedrock ridges and pools that clearly mark out the route of the floodwaters into the head of Ásbyrgi (Figs. 6/7B). At the 'upstream' (southern) end of the area are four smaller (100 m wide, 10 m high) amphitheatre-shaped cataracts that also open toward

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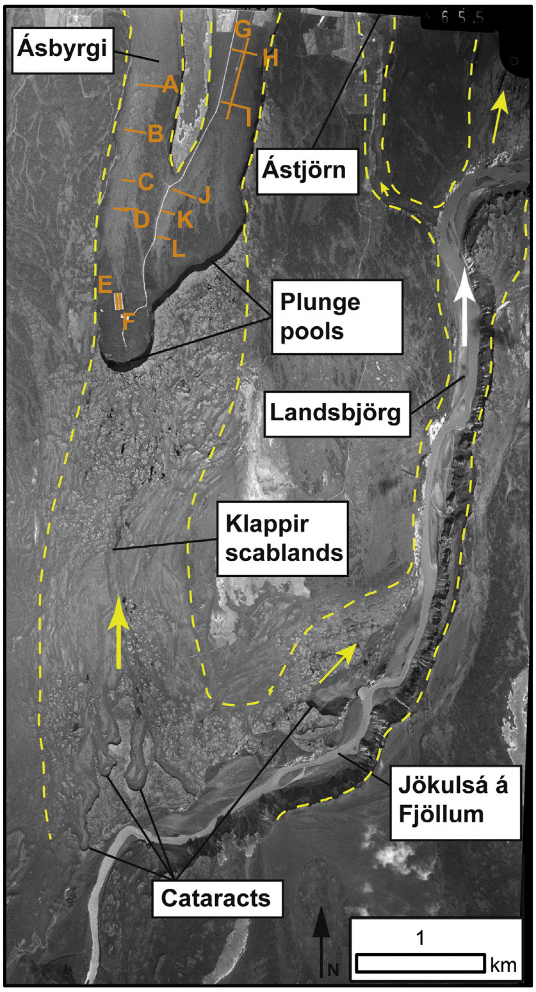

Fig. 6. Aerial photograph of the Klappir scablands and Ásbyrgi canyon. The present day course of the Jökulsá á Fjöllum is within the deeply incised main Jökulsárgljúfur canyon that flows to the east at Landsbjörg. Ásbyrgi is a large (3-km-long, 1-km-wide) horseshoe-shaped canyon cut into a northward-dipping lava succession with an island preserved between the two main channels. The yellow dashed lines indicate the areas that have been inundated by floodwaters, with the Klappir area of scabland topography with bedrock ridges and pools clearly visible. At the upstream limit of the scablands, four dry cataracts provide additional evidence for erosion during an extreme flood event in this area. The locations of the plunge pools at the apex of the western and eastern Ásbyrgi canyons are shown. The orange lines within Ásbyrgi indicate the location of the electrical resistivity tomography (ERT) surveys in the canyon floor, with letters corresponding to the profiles in Fig. 12. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Aerial photograph source: Landmælingar Íslands (adapted from Baynes et al., 2015).

the north (indicating flow direction from the south), which are located high (~90 m) above the current course of the river (Fig. 7). These cataracts include plunge pools at the base of the headwall featuring sediment ridges that could be interpreted as push-bars (Carling et al., 2009c); these bars show no obvious reworking since their formation (Fig. 7A). At the rim of Ásbyrgi, large-scale potholes (up to 10 m in depth) and flutes are clearly visible (Fig. 7C), and several notches (3–5 m in height) have been cut into the rim of the vertical headwall of the canyon (Fig. 8A). The exposure age of bedrock in one of these notches has been put at between 7.2 and 12.5 ka, indicating that Ásbyrgi and the Klappir scablands were formed during an extreme flood event in the early Holocene, shortly after deglaciation (Baynes et al., 2015).

The horseshoe of Ásbyrgi is made up of two parallel channels that have eroded back and coalesced (Fig. 6). Between the two parallel channels is 'Eyjan', or 'Island', a bedrock outcrop rising to the same elevation as the lava surface around the main rim of Ásbyrgi. The western canyon retreated farther south, and its headwall marks the location of the highest cliffs (90 m) in Ásbyrgi. At the base of the headwalls of the western and eastern canyons are large relict plunge pools (Fig. 8B). The floor of Ásbyrgi is covered in sediment, with many large boulders (some >3 m in diameter) found on the surface of the deposits (Fig. 8B). The maximum measured boulder size can be used to calculate the minimum discharge of the palaeo-flood that transported them (e.g., Costa, 1983; Clarke, 1996; Stokes et al., 2012). Caution should be employed when using such a method as different equations can give different estimates of flood discharge, and there are issues with the collection of the boulder size data and the interpretation of the resulting estimates (see discussion in Stokes et al., 2012). Within these caveats, we used the method described by Stokes et al. (2012) to calculate a rough estimate of the minimum flood discharge that would be required to transport the largest boulders in Ásbyrgi. The largest measured boulder in the eastern Ásbyrgi channel (diameter = 1.49 m) gives a minimum palaeo-discharge estimate of 12,000 $m^3\ s^{-1}$. In the western channel, where the diameter of the largest measured boulder is 3.75 m, the minimum discharge estimate is 39,000 $m^3\ s^{-1}$ (see Supplementary information for sensitivity analysis and full list of parametres used).

Small-scale fluvially sculpted bedforms on the top surface of the Island between the two eroded channels that make up the Ásbyrgi 'horseshoe' provide evidence that, pre-flood, the river flowed over the lava surface into which Ásbyrgi has been eroded (Fig. 9). Surveys from across the Island indicate a palaeo-flow direction that is consistently from the south (Fig. 9). These surfaces were formed before Ásbyrgi was eroded as the canyon walls cut straight across some of the landforms (Fig. 9B), and we propose that they were not formed during the flood as they are substantially smaller in scale (relief in the order of a few tens of centimetres) than the flutes, furrows, and potholes found at the rim of Ásbyrgi (relief in the order of a few metres, up to 10 m; Fig. 7C; Richardson and Carling, 2005). Similar-scale fluvial surfaces to those found on the Island are found on the eastern rim of Ásbyrgi and on the western rim of the modern canyon to the east (Fig. 6). During the last glacial period, the Icelandic ice sheet extended beyond the north coast of Iceland, covering the area containing Ásbyrgi and the Jökulsárgljúfur canyon (Norðdahl, 1990; Hubbard et al., 2006; Licciardi et al., 2007). During the retreat of the ice sheet across the central highlands, the discharge of the proto-Jökulsá á Fjöllum was likely greater owing to enhanced glacial ablation during deglaciation. Upstream of the Jökulsárgljúfur canyon, the Jökulsá á Fjöllum is at present a large braided river system (sometimes >1 km in width) flowing on a bedrock substratum; it is possible that the river developed such morphology all the way to the coast before the canyons were eroded. The fluvial surfaces on Ásbyrgi Island, on the eastern rim of Ásbyrgi and the western rim of the main canyon, indicate the palaeo-course of this system. Fluvial sediment is lacking on these surfaces, possibly because the sediment would have been entrained and transported during the early stages of the jökulhlaup before the surfaces were abandoned by the upstream propagation of the canyon headwalls.

4. Volume of rock eroded from Ásbyrgi and sediment depth

As demonstrated in Section 3.3, the evidence for extreme flood events at Ásbyrgi and the Klappir scabland area immediately upstream is clear. The landscape is disconnected from the course of the present day Jökulsá á Fjöllum, which now flows in a deeply incised canyon to the east at Landsbjörg (Fig. 6). The Klappir scablands and Ásbyrgi contain landforms preserved in pristine condition, unburied and with no evidence for fluvial modification through erosion since their formation, suggesting abandonment following the event that carved Ásbyrgi. Klappir and Ásbyrgi therefore provide an unusually good opportunity to examine the impact of a single extreme flood event in eroding bedrock and then in depositing sediment. Combined topographic analysis and near-surface geophysics surveys were used to evaluate the volume of bedrock eroded from Ásbyrgi and the thickness of sediment deposited during the waning stages of the flood.

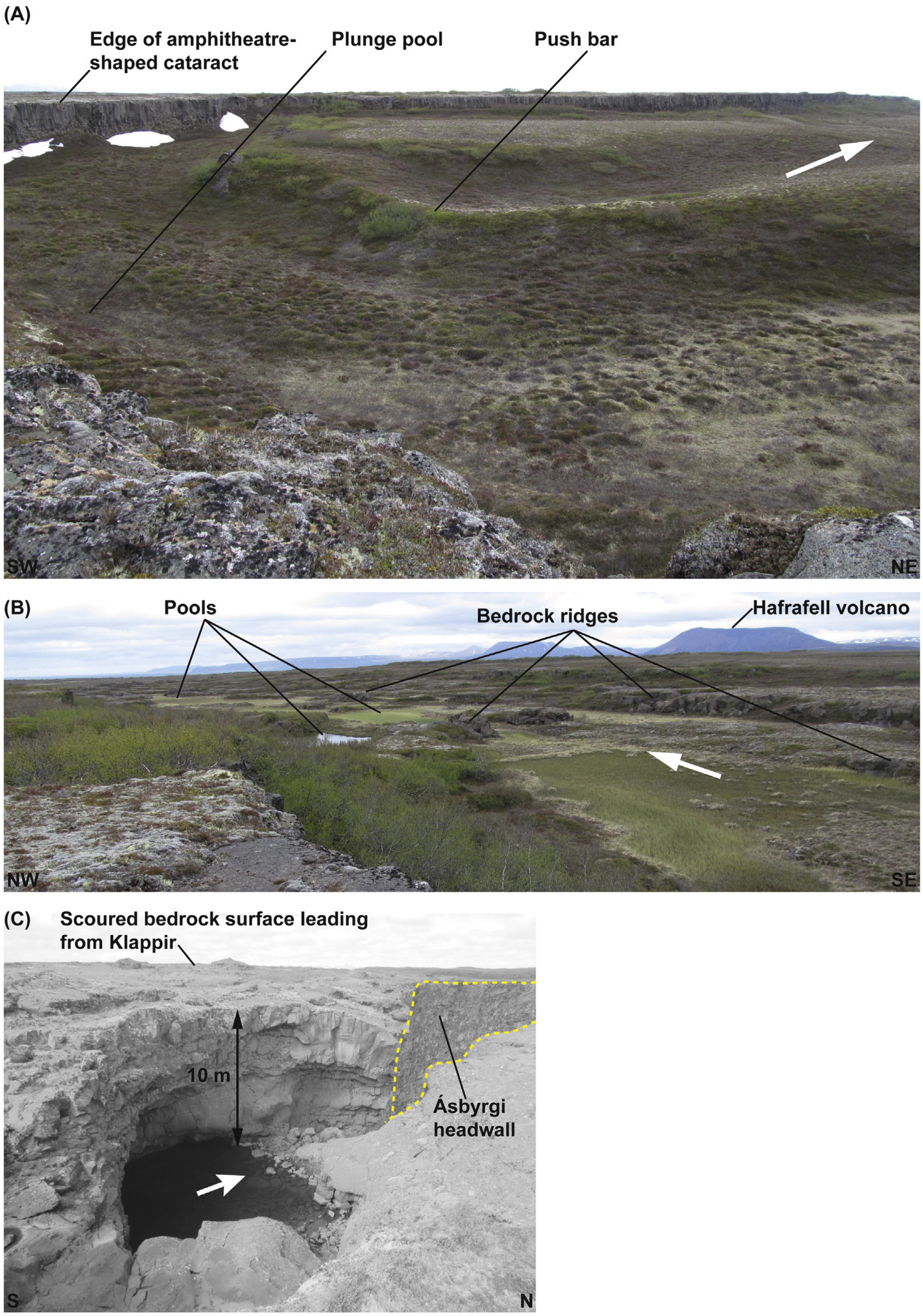

Fig. 7. Landforms in the Klappir scabland area suggest the action of powerful flows. In the south are three dry cataracts ~100 m wide with a 5–10 m vertical cliff at their head (A). Within the cataracts are arcuate sediment ridges that could be interpreted as push-bars preserved in pristine condition, showing no evidence for subsequent fluvial reworking. Downstream of the cataracts is an area with distinctive scabland morphology (B). Characterised by a series of bedrock ridges and pools (local relief ~5 m), this area clearly marks the route of the flood waters, as can also be seen in the aerial photograph (Fig. 6). White arrows indicate the direction of the floodwaters. Hafrafell, a nearby table-top volcano that erupted subglacially, is shown. The eruption age of Hafrafell has been dated to 11,100 ± 2200 years, thought to coincide with deglaciation in this area (Licciardi et al., 2007). (C) Megascale fluvial bedrock erosion landforms at the scoured rim of Ásbyrgi. Looking west into a 10-m-deep pothole within one of the eroded notches identified in Fig. 8, with flow direction to the north (white arrow). In the background of the photograph is the 90-m-high vertical headwall of Ásbyrgi (edge of rim highlighted in yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The volume of rock eroded from Ásbyrgi was quantified using high-resolution topographic data based on a total station survey and a 1.8-m resolution digital elevation model (DEM; source: TanDEM-X collected on 2 September 2012). A 'pre-flood' surface was constructed by interpolating the elevation values from around the outer rim and the Island surface across the top of the canyon. An initial estimate of the rock

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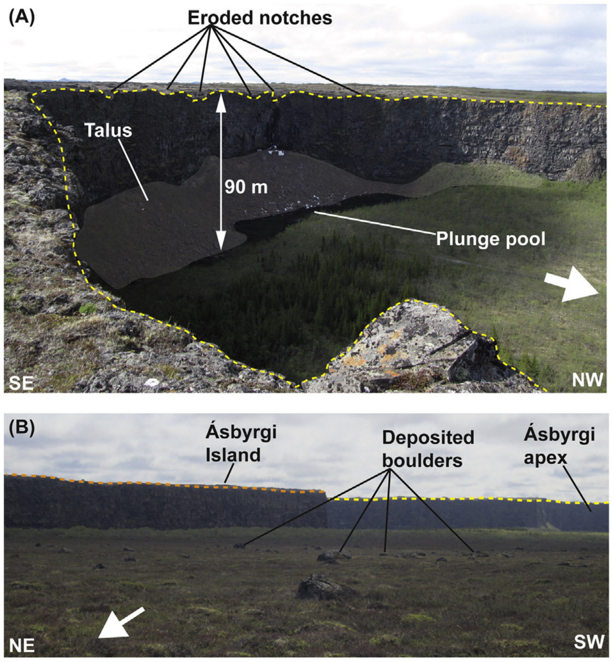

Fig. 8. Ásbyrgi canyon is a horseshoe-shaped cataract cut into a northward-dipping lava succession. The vertical headwall at the apex of Ásbyrgi is 90 m high with a large plunge pool at the base and a pile of sediment deposited immediately downstream (A). Several eroded notches are present along the rim of the canyon (canyon edge highlighted with yellow dashed line). At the base of the headwall, talus deposits resulting from rockfalls show no evidence for reworking by overland flow. (B) Looking into the western canyon of Ásbyrgi from near the canyon outlet. The rim of the main canyon is highlighted in yellow and the rim of the Ásbyrgi Island is shown in orange. The floor of Ásbyrgi is covered in sediment including large boulders (some >3 m in diameter). No evidence for recent flow within the canyon exists so it is hypothesised that these boulders were deposited following transportation during an extreme flow. The source of the boulders is impossible to determine, but we suggest that they were initially part of the lava succession into which Ásbyrgi has been cut rather than transported from farther upstream. From this we propose that the floodwaters that formed Ásbyrgi were powerful enough to transport boulders of 3 m in diameter. White blocky arrows indicate palaeo-flow direction (to the north). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

eroded from Ásbyrgi during formation was made through the subtraction of the 'pre-flood' surface from the 'present day' DEM (Fig. 10A), giving a total of 0.139 km^3. However, this is an underestimate of the true amount of rock eroded from Ásbyrgi as the floor of the canyon is completely covered with sediment. An assessment of the sedimentary thickness was carried out using electrical resistivity tomography (ERT) surveys across the canyon floor. The ERT surveys are nondestructive and provide greater spatial coverage than point measurements when multiple profiles are collected. The ERT is an established method for imaging the near subsurface and has been used for a wide range of applications, including detecting the bedrock-sediment interface (Hsu et al., 2010; Chambers et al., 2012), aquifer characterisation (Doetsch et al., 2012), detection of subsurface cavities (Martinez-Lopez et al., 2013), rockwall retreat rates (Siewert et al., 2012), and permafrost depth and structure (You et al., 2013). The ERT surveys were carried out across transects A–L shown in Fig. 6, with 25 electrodes at 5-m spacing, allowing electrode spacings ranging from 5 to 40 m. By increasing the spacing between the electrodes, the current penetrates deeper, building up a data section that can be interpreted in terms of lateral and depth variations in electrical resistivity. Some of the transects were built up from multiple surveys in order to cover a longer distance than the 120 m possible in a single 25-electrode survey, such as the long transect along the middle of the eastern canyon (transect G, 680 m long; Fig. 6).

Different inversion methods are available in the 'res2Dinv' software (res2Dinv version 3.4; Geotomo, 2001). The conventional least squares method minimises the square of the difference between the measured and the calculated apparent resistivity values and produces a model with smooth resistivity variations (Loke et al., 2003). However, the technique is not perfectly appropriate when the subsurface contains sharp boundaries between resistivity interfaces as the smoothing of the boundaries between layers makes their localisation difficult. We therefore employed a 'robust iterative inversion' to model our survey data, whereby the absolute changes in the resistivity values are minimised (Claerbout and Muir, 1973). This approach produces models of the subsurface with sharp interfaces between different subsurface structures that have different resistivity values (Loke et al., 2003) and was deemed most appropriate because we expect to see a sharp boundary between the sediment deposits and the basalt bedrock beneath; all images presented here have been produced using this method (Fig. 11). The model iterations were stopped when the percentage misfit between the measured and the calculated apparent resistivity was <5% or no further improvement to the fit was possible with further iterations. In the case of transect E, no further improvement to the fit occurred after five iterations, when RMS error was 5.9%.

Broadly, sedimentary deposits have the lowest resistivity and igneous rocks the highest (Telford et al., 1990). We therefore interpret the bedrock-sediment interface in each of our profiles as the sharp horizontal downward transition from regions of low to high resistivities (Fig. 11). The typical range of resistivity for basalt is large: 10^1–1.3×10^7 Ωm (Telford et al., 1990) because of a number of factors, including the water content in fractures and pore space. The resistivity of dry (0% water content) basalt is 1.3×10^7 Ωm, whereas basalt with 0.95% water content typically has a much lower resistivity of 4×10^4 Ωm (Telford et al., 1990). The peak resistivity in each of our surveys is up to 3.7×10^3 Ωm, which implies that the basalt in our study area has a water content >1%. This is to be expected as the rocks are located in a coastal region with a wet climate. We are confident that the transition to high resistivity found a few metres below the surface is the top of bedrock (Fig. 11). The layer of lower resistivity at the base of each of the surveys is interpreted to represent the water table owing to its broadly consistent depth at ~15 m across all surveys.

The ERT surveys show that the sediment is ~1 m thick across the floor of the western gorge (Figs. 11A–D) and 3 m thick in the eastern gorge (Figs. 11G–I). Owing to forest cover, only two surveys were carried out in a field near the apex of the western gorge, but these show that the sediment in this region of the canyon is ~5 m thick (Figs. 11E–F). We hypothesise that this is because of the survey location on top of the pile of sediment immediately downstream of the plunge pool. These surveys were parallel to each other and have produced a similar subsurface morphology despite a slight difference in the peak resistivity values, indicating reproducibility of the results. The three surveys undertaken in the region between the two main channels indicate a sediment depth of ~1.5 m in this region (Fig. 11J–L).

Sediment depths were interpolated across the canyon floor using the 'Spline with Barriers' function in ArcGIS (Fig. 10B). Owing to the limits on the spatial coverage of the ERT surveys, the interpolated surface does not cover the canyon floor in the apex of the western channel of Ásbyrgi or in some of the areas at the exit of the western and eastern canyons. The volume of sediment within Ásbyrgi was estimated by subtracting the interpolated surface from the DEM of the canyon floor topography, giving a volume of 0.005 km^3, making up <4% of the total volume of rock eroded from Ásbyrgi at 0.144 km^3. This is a minimum estimate as the interpolated surface does not cover the entire floor of Ásbyrgi, although the additional sediment located beyond the interpolated surface is unlikely to cause a significant increase in the estimate of total rock eroded. Fig. 10C shows the bedrock surface elevation above sea level, created by subtracting the interpolated sediment depth (Fig. 10B) from the DEM of the canyon floor. The area close to the apex of Ásbyrgi is affected by the presence of trees that are picked up by the DEM (the highest elevation areas in blue) but farther north, near to the outlet of the two canyons, the elevation of the bedrock surface above sea level is

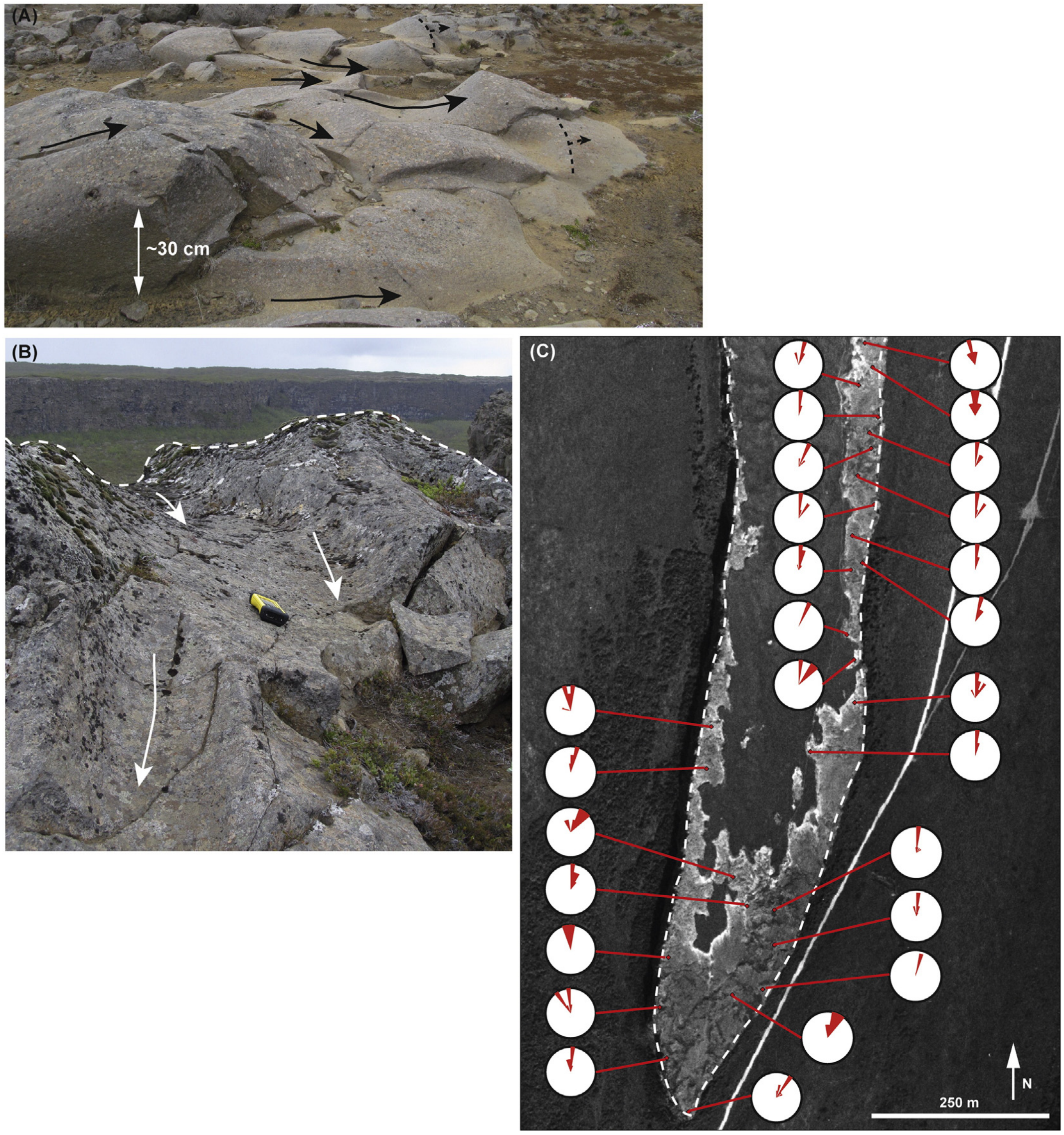

Fig. 9. Evidence for palaeo-flow on Ásbyrgi Island. (A) The morphology of the flutes and furrows allows the identification of the flow direction of the palaeo-river that formed them. Flutes and furrows (solid black lines) are parallel to the flow direction; dashed lines represent the crests of upstream-facing convex surfaces that are perpendicular to the palaeo-flow (Wilson and Lavé, 2014). Flow-direction is to the north. Local relief of bedrock surface is ~30 cm. (B) The landforms atop the Island between the two Ásbyrgi canyons were formed before the canyon was carved because the flutes and furrows lead right to the edge of the vertical walls (white dashed line). Photograph looking southeast on eastern edge of the Island. For scale, dimensions of GPS unit are 17 × 9 × 4 cm. C. Aerial photograph (source: Landmælingar Íslands) of the apex of Ásbyrgi Island (outline shown by dashed white line) showing the palaeo-flow direction of the fluvially sculpted bedrock features from 27 survey locations (total measurements = 182). All of the sites indicate a palaeo-flow direction broadly to the north.

very similar. This observation suggests that when the two canyons were retreating, before they coalesced, the vertical knickpoints at the headwall of the canyon were the same height.

5. Discussion

Some of the features described in Section 3, such as boulder erratics, are not exclusive to the action of extreme flood events and individually should not be used as evidence for the action of extreme flood events (Carling et al., 2009c; Carrivick et al., 2013). However, as multiple different landforms across all scales of the Carrivick et al. (2004) criteria are found in three distinct and very different reaches of the Jökulsárgljúfur canyon, we suggest that the evidence for extreme flood events is unequivocal in this landscape. Combining this with the identification of three significant periods of canyon cutting by Baynes et al. (2015) at ~10,000, ~5000 and ~2000 years ago, the following sections reconstruct the landscape evolution of the lower Jökulsá á Fjöllum during the Holocene.

5.1. Model of formation of Ásbyrgi and Klappir during a flood ~10,000 years ago

The presence of fluvially sculpted surfaces on the top of Ásbyrgi Island as well as strath terraces above the Jökulsárgljúfur canyon to the east suggests that during the retreat of the last Icelandic ice sheet, a major river flowed from the south over the northward-dipping lava surface into which the canyons have been eroded. This proto-Jökulsá á Fjöllum may have been substantially wider than the modern river channel as the discharge may have been higher because of increased meltwater generated during a major period of deglaciation. It possibly generated a large braided river system with multiple active channels on the lava substrate similar to the present day Jökulsá á Fjöllum upstream of Selfoss. This palaeo-river system could have simultaneously

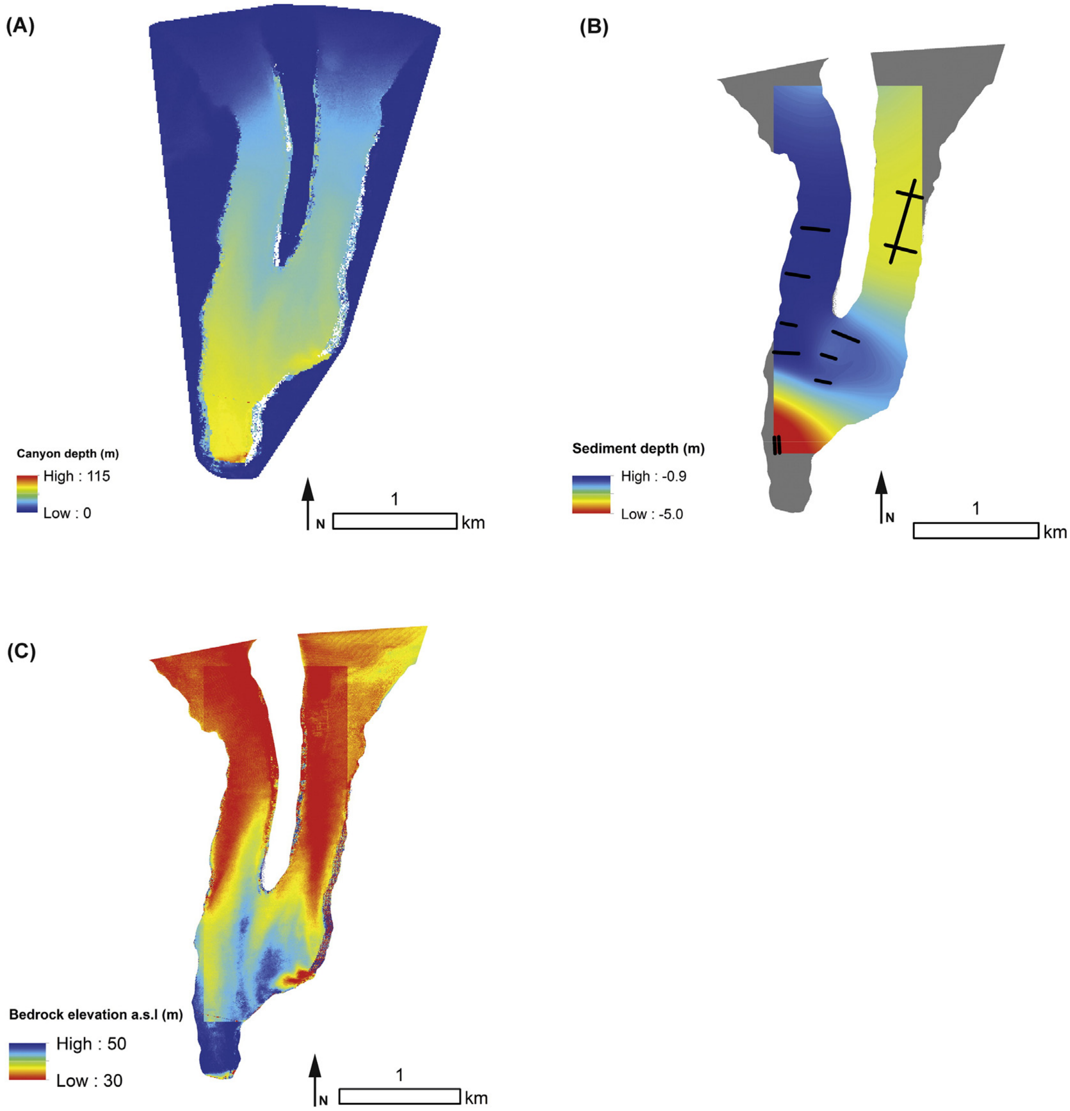

Fig. 10. (A) Depth of Ásbyrgi canyon calculated by subtracting the DEM of the 'pre-flood' top surface interpolated from elevation values around the outer rim and the Island and the DEM of the present day canyon. The total volume of rock eroded between the two DEMs, without accounting for the deposited sediment in the floor of Ásbyrgi, is 0.139 km^3. (B) Interpolated sediment depth to the floor of Ásbyrgi from the ERT data using the 'spline with barriers' function in ArcGIS. This surface is used to calculate a minimum estimate of the sediment deposited within Ásbyrgi through a comparison with the DEM of the canyon floor (0.005 km^3). The areas at the exit of the canyon are not considered owing to the spatial coverage of the ERT surveys (black lines) and the processing extent of the interpolation algorithm. C. Elevation of bedrock above sea level. Beyond the processing extent of the interpolation algorithm, the bedrock elevation is represented by the DEM of the canyon floor.

occupied, and fluvially sculpted, the surface at the top of Ásbyrgi Island and the surface close to the present day main canyon (Fig. 12A). Alternatively, the palaeo-river system could have been similar in size to the present day Jökulsá á Fjöllum and could have migrated the 2.5 km across the lava surface, sculpting the two bedrock surfaces at different times (Fig. 12A).

During the initial phases of the early Holocene jökulhlaup, the floodwaters spread across the Klappir area and the area to the east, over what would become the course of the modern day river. The eastern floodwaters split, and two canyons (the origins of the main Jökulsárgljúfur canyon at Landsbjörg and lake Ástjörn) began to be incised through the plucking and toppling of large basalt blocks and columns at the lava flow front (Fig. 12B). The floodwaters in the Klappir area also began incising at the lava flow front with two canyons forming close to each other (the beginnings of the modern Ásbyrgi canyon) (Fig. 12B). Upstream of these four main canyons, the Klappir area began to be sculpted into the ridge and pool scabland morphology seen today, with the smaller cataracts starting to be formed under a similar process to the main canyons to the north.

Fig. 12C shows the proposed locations of the canyons midway through the jökulhlaup, with the floodwaters flowing into the Ástjörn canyon captured owing to the upstream migration of the head of the main Jökulsárgljúfur canyon farther east. We propose that the jökulhlaup had no further impact on the scabland tract leading to Lake Ástjörn, which is now exposed ~60 m above the modern channel (Fig. 12C). The two canyons of Ásbyrgi were also still retreating at the mid flood stage (Fig. 12C); and at some point during the latter stages of the flood, the two canyons coalesced to form the horseshoe-shaped canyon seen today (Fig. 12D). Based on the maximum size of boulders deposited across the canyon floor, calculations suggest that the discharge of the jökulhlaup that eroded Ásbyrgi was at least 39,000 $m^3\,s^{-1}$, although it may have been greater than this magnitude. The perfect preservation of landforms in the Klappir scablands and the maintained vertical headwall of Ásbyrgi suggest that the floodwaters were diverted from this area at the end of the flood, and we propose that this occurred through the capture of the waters because of the retreat of the headwall of the main Jökulsárgljúfur canyon to the east (Fig. 12D). The ERT profiles reveal that the sediment in the canyon

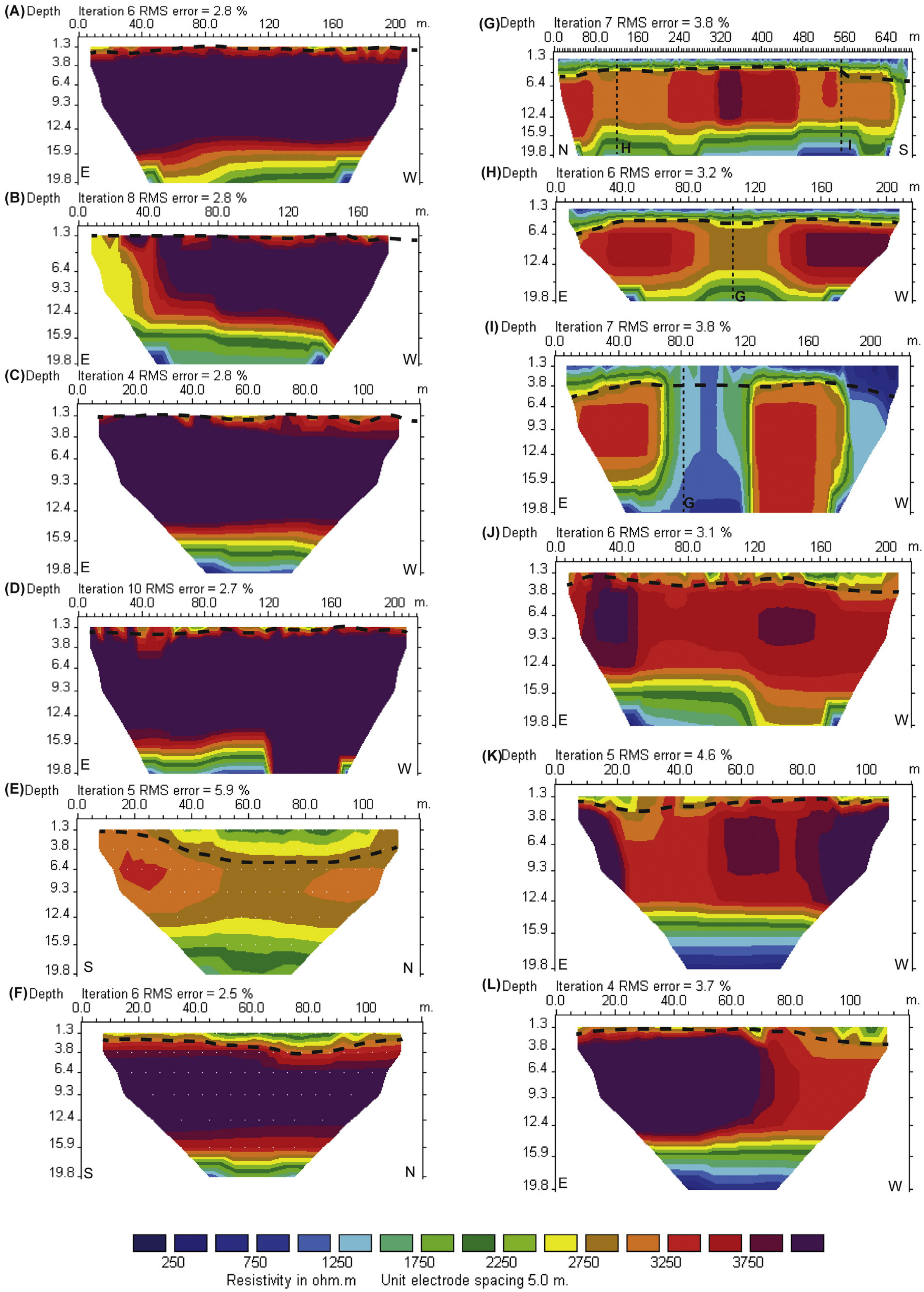

Fig. 11. Electrical resistivity tomography imaging of the subsurface. Labels (A–L) refer to the location of each transect shown in Fig. 6. Surveys A–D are from the western canyon; they show a depth to the bedrock-sediment interface of ~1 m. Surveys E and F are parallel to each other from the field close to the apex of Ásbyrgi; they show a sediment thickness of ~5 m. Survey G is a longitudinal survey along the middle of the eastern canyon with surveys H and I also from the eastern canyon, each showing a uniform sediment thickness of ~3 m. Surveys J–L are from the region between the two main canyons and have a sediment depth of ~1.5 m. The letters at the edges of each profile (bottom) indicate the orientation of the transects. Vertical dashed lines and corresponding labels on (G), (H), and (I) indicate the location where the transects cross each other.

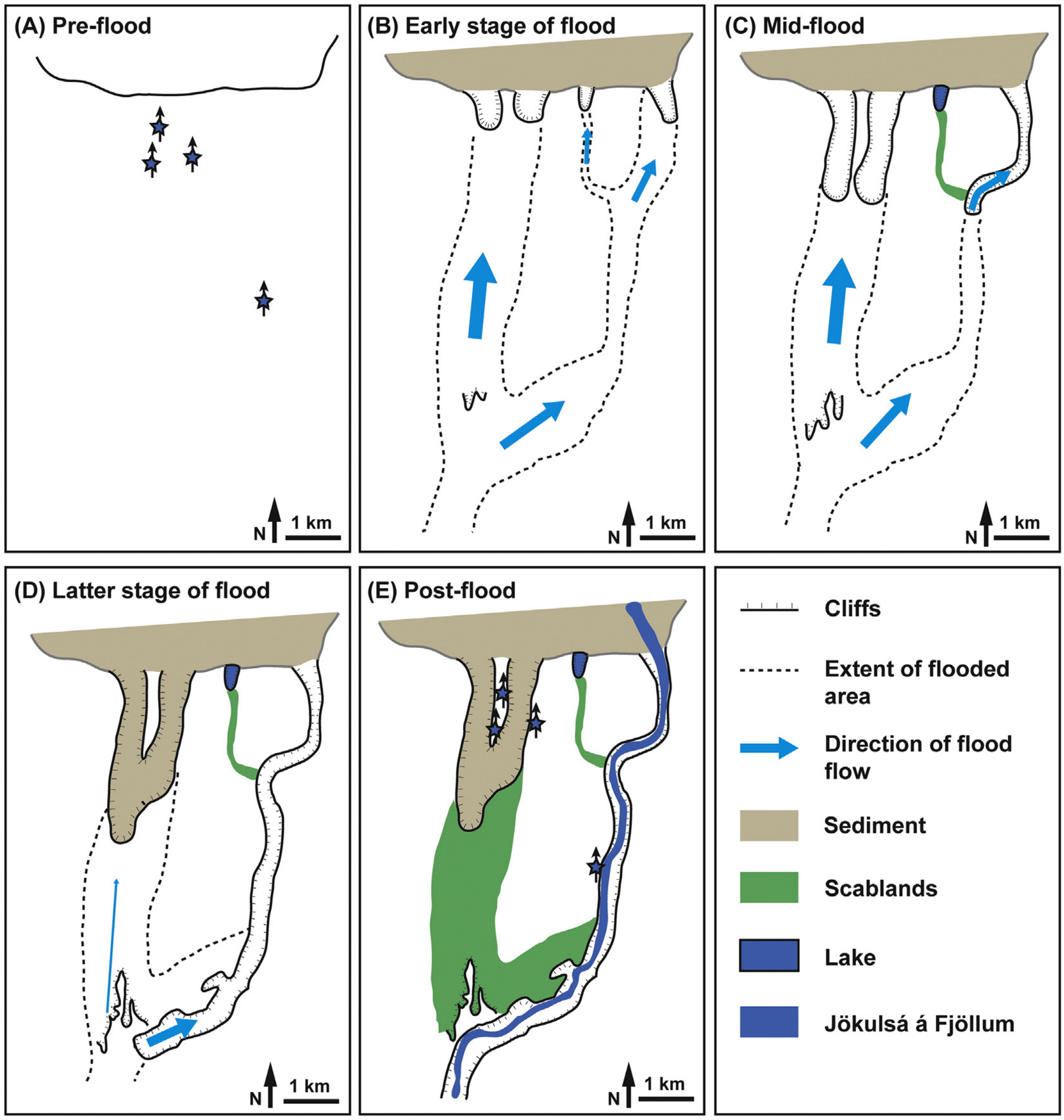

Fig. 12. Proposed macroform evolution of the lower Jökulsárgljúfur canyon during an extreme flood event in the early Holocene. (A) Before the flood, the precise course of the Jökulsá á Fjöllum is impossible to determine; but fluvially sculpted surfaces on the top of Ásbyrgi Island, the eastern rim of Ásbyrgi, and the western rim of the main canyon at Landsbjörg indicate that a river once flowed here before the canyons were formed. The locations of the fluvially sculpted surfaces are shown by the blue stars (also shown in E for comparison), with direction of palaeo-flow shown by the black lines. (B) In the early stages of the flood, the floodwaters follow the course of the pre-flood river and also spread to the east. At the northern limit of the lava surface, four canyons begin to be incised. Through time, the floodwaters flowing into the canyon that currently contains Lake Ástjörn are captured by the faster retreat of the canyon to the east (C) while the two Ásbyrgi canyons continue to retreat until they coalesce. The western canyon of Ásbyrgi continues to retreat and, eventually, the large canyon to the east retreats far enough to also capture the floodwaters flowing across the Klappir scablands into Ásbyrgi. During the waning flow, a thin layer of sediment is deposited in the bottom of Ásbyrgi (D). The headwall in the main canyon continues to retreat, disconnecting Ásbyrgi and Klappir from the course of the Jökulsá á Fjöllum leading to the outstanding preservation of the landforms (E). Subsequent floods along the Jökulsá á Fjöllum are channelled in the main canyon, although some potential minor reoccupation of Klappir may have occurred, which stripped some of the soils (Waitt, 2002). The main canyon at Landsbjörg is drawn here assuming that all the erosion in this main canyon occurred during the early Holocene flood, although additional reworking of the canyon morphology during later floods cannot be ruled out.

floor is just a thin veneer only a few metres thick over the bedrock surface, filling <4% of the total volume. We propose that this sediment was deposited across the canyon floor of Ásbyrgi during the latter stages of the flood when the waning floodwaters were no longer powerful enough to transport the sediment load (Fig. 12D).

Waitt (2002) proposed that the eroded scabland area immediately upstream of Ásbyrgi was reoccupied during the late Holocene flood ~1500 years ago as the soil in this area lacks the H3 (~2900 YBP), H4 (~3800 YBP), and H5 (~6000 YBP) tephra layers, while the soil beyond the scabland limits do contain them. This observation suggests that the soils in the scabland area were washed away after the deposition of the H3 layer, most likely during the late Holocene flood. However, the exposure age from the eroded notch at the rim of Ásbyrgi (9850 ± 2650 years from a sample in a notch a couple of metres under the original surface of the lava flow; Baynes et al., 2015) suggests that any flow through here during the mid- and late Holocene was not powerful enough to cause any significant bedrock erosion (i.e., not enough to 'reset' the concentration of cosmogenic nuclides). Thus, we can be confident that the carving of Ásbyrgi represents the impact of an early Holocene flood event. The effect of any mid- or late Holocene floodwaters that overtopped the scablands and flowed into Ásbyrgi on the sediments deposited across the canyon floor is unknown, but the presence of the eroded boulders (from the early Holocene flood) and the thin layer of canyon floor deposits suggest that at least some of the material was preserved. The loss of additional material through aeolian processes is unlikely because of the morphology of the canyon and the vegetation cover.

Over time, overland flow into a canyon with a vertical headwall should act to diffuse the knickpoint through abrasion and plucking of small blocks (Lamb et al., 2014). As the Ásbyrgi headwall is vertical and contains no evidence for diffusion since its formation, we propose that the Klappir scablands and Ásbyrgi were formed during a single extreme flood event. The floodwaters were diverted at the end of the flood preventing further fluvial activity that could have diffused the canyon headwall or reworked the landforms present on the Klappir scablands. Fig. 12E shows the state of the landscape at the present day, which is likely to be very similar to that of the immediate aftermath of the early Holocene flood, although the morphology of the main canyon at Landsbjörg may have been altered after the early Holocene flood owing to subsequent modification during moderate and large floods in the mid- and late Holocene.

5.2. Evolution of lower Jökulsá á Fjöllum during mid-late Holocene floods

While we hypothesise that the knickpoint at the head of the main Jökulsárgljúfur canyon retreated at least as far as to capture the floodwaters flowing into Ásbyrgi, we have no evidence to suggest the exact position of the knickpoint at the end of the early Holocene flood. Waitt (2002) stated that the canyon already existed before the eruption of a fissure at Hljodaklettar ~9000 years ago, as some of the cinder cones lie within the canyon (Fig. 1C). This chronology supports the theory that an early-Holocene flood, pre-fissure eruption, initiated formation of the Jökulsárgljúfur canyon and that erosion through headwall retreat proceeded at least as far as Hljodaklettar. We suggest that the 16 floods identified by Waitt (2002) and Kirkbride et al. (2006) at Vesturdalur have contributed to the upstream propagation of the knickpoint(s) from Hljodaklettar to the current apex of the Jökulsárgljúfur canyon. The two youngest floods dated by Kirkbride et al. (2006), as well as a late Holocene extreme flood that several authors agree has taken place (Sæmundsson, 1973; Tómasson, 1973; Helgason, 1987; Waitt, 2002), led to significant erosion within the upper 5 km of the canyon (Baynes et al., 2015). Additional erosion of the downstream reach of the main canyon during the mid- and late Holocene floods cannot be ruled out, but we believe that this is minimal because of the absence of active, or relict, knickpoints within this part of the canyon. An abandoned terrace on the east side of the canyon at Landsbjörg represents a historical position of the river bed (Fig. 6), but the age of formation and abandonment of this terrace is not currently known.

6. Conclusions

Our work documents widespread evidence for bedrock erosion during extreme flood events in the lower Jökulsá á Fjöllum in northern Iceland. Multiple discrete phases of extreme flooding have occurred during the Holocene, leaving a lasting legacy on the landscape morphology in three distinct reaches. Evidence for erosion during extreme floods is clear at Dettifoss and Ásbyrgi, while evidence for deposition is found in the Forvoð valley. Ásbyrgi, unaltered since formation, contains a thin veneer of sediment in the floor of the canyon documented using an ERT survey; sediment fills <4% of the total 0.14 km^3 volume of material that was eroded during an early Holocene extreme flood event, with reconstructed discharge of at least 39,000 m^3 s^{-1}. During this flood, coincident erosion was occurring in what is now the main Jökulsárgljúfur canyon through upstream migration of the canyon headwall. The canyon head retreated far enough to capture the floodwaters flowing across the Klappir scablands into Ásbyrgi; all future flow of the Jökulsá á Fjöllum and all subsequent floods were channelled within the main canyon at Landsbjörg to the east and caused significant erosion farther upstream, although a small-scale overtopping over Klappir during later floods cannot be ruled out. The overall contribution of extreme flooding along the Jökulsá á Fjöllum during the Holocene has been the formation of a 28-km-long, up to 100-m-deep canyon in <10 ka. This highlights the importance of extreme flood events in the erosion of bedrock landscapes, with discrete high-magnitude events having the potential to cause catastrophic landscape change that can be preserved over millennial timescales.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.geomorph.2015.05.009. These data include the Google map of the most important areas described in this article.

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